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ESTIMATION OF THE EFFECTS OF A SHIP'S STEAMING ON THE FAILURE RATE OF ITS EQUIPMENT: AN APPLICATION OF ECONOMETRIC ANALYSIS

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ABSTRACT

Regression analysis is used to estimate the effects of a ship's steaming on the failure rate of its equipment, holding constant the effects of other factors such as a ship's class, fleet, time since overhaul, and point in the deployment cycle. Equipment failures are measured with data on 14,000 CASREPTs for destroyer-type ships in 1970-75. It is widely thought that steaming would increase the number of equipment failures because of more wearout. However, we find the failure rate of equipment seems to decrease with steaming in the long run.

ACKNOWLEDGMENTS

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INTRODUCTION

Increases in the price of fuel have caused the Navy to reduce steaming by about 25 percent since 1974. There is widespread feeling that the readiness of the fleet should have been affected. It is usually felt that the operational performance of a ship's crew, i.e., its "training readiness," would be impaired because of fewer training exercises, but that the equipment condition of a ship might be improved because of less wearout. Thus, the net effect on readiness is thought to be unclear.

The purpose of this study is to estimate the effects of steaming reductions on a ship's readiness. However, because data are unavailable to study training readiness, we focus on the condition of a ship's equipment.

A CASualty REPorT or CASREPT is filed when a ship has a serious equipment failure requiring more than four days to repair. Data on 14,000 CASREPTs are used to measure equipment failures; the CASREPTs occurred in 1970-75 on 91 destroyer-type ships, i.e., destroyers, cruisers, and frigates.

Regression analysis is used to estimate the effect of steaming on the number of CASREPTs occurring each month, i.e., the CASREPT rate. Lack of data on explanatory factors is a serious problem, however. We try to overcome this problem by using various econometric techniques. Numerous proxy variables are used as measures of causal factors. Separate models are estimated for the less serious C2 CASREPTs, as well as the more serious C3 and C4 CASREPTs. We also use different estimation procedures, i.e., ordinary least squares and least squares with dummy variables, and different data sets, i.e., pooled time series cross section and cross section.

We find no evidence to support the hypothesis that steaming impairs equipment condition. Instead, steaming or factors associated with it seem to enhance equipment condition. Since steaming reductions are also likely to reduce training readiness, the two effects on readiness appear to be reinforcing rather than opposing. Thus, steaming reductions clearly impair the readiness of the fleet.

METHOD

REGRESSION MODEL SPECIFICATION

Through a literature review and discussions with Navy personnel, we identified "direct determinants" of the CASREPT rate. These are listed below together with the expected direction of their effects on the CASREPT rate.

1. Past utilization of equipment (+)
2. Current utilization of equipment (+)
3. Age of equipment (+)
4. Degree of equipment complexity (+)
5. Favorable external conditions (-)
6. Condition of equipment after overhaul (-)
7. Training of personnel (-)
8. Number of equipment starts (+)
9. Initial stock of parts on board (-)
10. Funds allowance for parts (OPTAR funds) (-)
11. Willingness of command to report CASREPTs (+)

Data are unavailable on most of these determinants. To overcome data problems, we identified relationships between determinants and measurable explanatory variables. These relationships are given below. If we could identify it, the direction of an explanatory variable's effect on a direct determinant is indicated.

1. Past utilization of equipment (+):

Past steaming underway (+)[1]

Past steaming not underway (+)

Time since overhaul (+)

2. Current utilization of equipment (+):

   Current steaming underway (+)

   Current steaming not underway (+)

3. Age of equipment (+):

   Months since overhaul (+)

4. Degree of equipment complexity (+):

   Ship class (?)

5. Favorable external conditions (-):

   No measurable explanatory variables identified

6. Condition of equipment after overhaul (-):

   Atlantic or Pacific Fleet (?)

7. Training of personnel (-):

   Current steaming underway (+)

   Current steaming not underway (+)

   Past steaming underway (+)

   Past steaming not underway (+)

   Time since overhaul (+)

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[1]Hours of steaming underway is a measure of operating tempo: the crew is relatively active operating the ship and undertaking training exercises. Hours steaming not underway are periods of relative inactivity. Although energy needs are met from its own boilers, ship systems are operated at a slower pace and the crew undertakes fewer training exercises. Hours not steaming are periods of minimum activity: ship's boilers are turned off and energy is provided from shore through an electrical hookup.

8. Number of equipment starts (+):

   No data available

9. Stock of parts on board (-):

   Fleet (?)

   Time since overhaul (-)

10. Funds allowance for parts (OPTAR funds) (-):

    Fleet (?)

11. Willingness of command to report CASREPTs (+):

    Fleet (?)

    Point in the deployment cycle:

       Months 1,2,3 and 4 after overhaul (+)

       Months 1,2,3 and 4 prior to overhaul (-).

This system of structural relationships was solved in terms of measurable explanatory variables. The result is a reduced form regression model having the variables listed in table 1. We also include "number of months since January 1970" to test for time trends.

By specifying theoretical relationships, we are able to identify explanatory variables, such as past and current steaming, that may affect the CASREPT rate. However, except for the dummy variables, months 1, 2, 3 and 4 after and before overhaul, the direction of a regression variable's effect cannot be predicted a priori, a result which may not critically depend on our particular specification of relationships between explanatory variables and

TABLE 1

DEFINITIONS, MEAN VALUES AND STANDARD DEVIATIONS OF CASREPT RATE MODEL VARIABLES

Variables	Mean values	Standard deviations
Monthly number C2 CASREPTs	4.14	3.61
Monthly number C3/C4 CASREPTs	1.55	1.89
Monthly steaming hours underway	247.84	197.2
Total past steaming hours underway since overhaul	5576.7	2996.5
Monthly steaming hours not underway	139.4	131.2
Total past hours steaming not underway since overhaul	3653.0	2306.4
Number of months since Jan 1970	20.4	12.3
Number of months since overhaul	22.1	12.0
Overhaul cycle variables:		
One if first month after overhaul, zero otherwise	0.016	.12
One if second month after overhaul, zero otherwise	0.017	.13
One if third month after overhaul, zero otherwise	0.017	.13
One if fourth month after overhaul, zero otherwise	0.017	.13
One if first month before overhaul, zero otherwise	0.034	.18
One if second month before overhaul, zero otherwise	0.034	.18
One if third month before overhaul, zero otherwise	0.034	.18
One if fourth month before overhaul, zero otherwise	0.033	.18
Ship classes:		
FRAMS: Benchmark ship class	0.32	.47
DD 931	0.079	.27
DDG 2	0.18	.38
DDG 31	0.019	.14
DDG 35	0.018	.13
DDG 40	0.0073	.085
FF 1036 One if in ship class, zero otherwise	0.0073	.085
FF 1037	0.073	.26
FF 1040	0.095	.29
FF 1052	0.041	.20
FFG 1	0.026	.16
CG 16	0.049	.22
CG 26	0.084	.28
Fleet: One if Atlantic, zero otherwise	0.48	.50

determinants.[1] Signs of regression variables are ambiguous because each is related to several direct determinants which have different effects qualitatively. These real world complexities make it impossible to understand the reasons for the measured effect of a regression variable.

Because of less wearout, equipment condition was thought to improve with steaming. However, our reduced form equation shows that many positive and negative factors could be affected which makes the total effect of steaming unclear theoretically. For example, by reducing the crews' skill in using complex equipment, less steaming could cause more operator induced equipment failures.[2] The net effect of less steaming depends on whether positive effects on factors such as wearout outweigh negative effects on factors such as operators' competence.

Regression analysis is used to estimate the net effect of steaming on the CASREPT rate. Unfortunately, as we have noted above, we cannot determine from simply the sign of steaming variables, which

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[1]An alternative system of relationships probably also would yield ambiguous theoretical results.

[2]This is an example of how training of personnel might be affected. In the language of the model, less steaming leads to less training which results in more CASREPTs per month.

underlying determinants cause it to have a beneficial effect on the CASREPT rate.

Findings

Pooled time series cross section data on 2468 ship-months are used to analyze the CASREPT rate for C2 and C3/C4 CASREPTS. Regression results, given in table 2, are obtained using the ordinary least squares estimate procedure.

The F statistics indicate both regressions are statistically significant at the .01 level. The R^2s of 0.140 for C2 and 0.0957 for C3/C4 CASREPTs are low but not unusual for models estimated wth time series cross section data. Low R^2 values indicate that about 90 percent of the variation in the CASREPT rate is unexplained. A large fraction of serious equipment failures is still random, but some of it can be explained.

Our major finding is that past steaming has a statistically significant and important beneficial effect on the CASREPT rate. This variable's high t-values of 6.5 for C2 and 4.4 for C3/C4 CASREPTs indicate that the regression coefficients are statistically significant at the .05 level.

The "elasticity" is the percent change in a dependent variable due to a one percent change in an explanatory variable. If the elasticity equals one in absolute value, a variable has a

TABLE 2

CASREPT RATE REGRESSION FINDINGS

Variable	C2 Effect[a]	C2 Elasticity[b]	C3/C4 Effect[a]	C3/C4 Elasticity[b]
Current hours steaming underway per month	.00216 (5.7555)[c]	.12923	.00008 (.3912)	.01259
Total past steaming hours underway since overhaul	-.00049 (6.52165)[c]	-.66163	-.00018 (4.3961)[c]	-.63926
Current hours steaming not underway per month	.00143 (2.4533)[c]	.04822	.00104 (3.30056)[c]	.09298
Total past hours steaming not underway since overhaul	-.00013 (1.6323)	-.11474	-.00001 (.2218)	-.02235
Number of months since Jan 1970	-.00205 (.2281)	-.01009	.00128 (.2651)	.01680
Number of months since overhaul	.12909 (5.4296)[c]	.68802	.05842 (4.57923)[c]	.83170
Dummy variables:				
First month after overhaul	1.11332 (1.9553)[c]		.45678 (1.4950)	
Second month after overhaul	.06988 (.1264)		.27744 (.9356)	
Third month after overhaul	-.29071 (.5324)		.03801 (.1297)	
Fourth month after overhaul	-.07861 (.1452)		-.28703 (.9882)	

TABLE 2 (Cont'd)

Variables	C2 Effect[a]	C3/C4 Effect[a]
First month before overhaul	-2.11825 (5.2371)[c]	-.83522 (3.84576)[c]
Second month before overhaul	-1.07911 (2.7201)[c]	-.47636 (2.23779)[c]
Third month before overhaul	-.73260 (1.8687)[c]	-.58172 (2.76527)[c]
Fourth month before overhaul	-.50262 (1.2795)	-.11158 (.5483)
DD 931	1.81859 (6.6534)[c]	.00901 (.0615)
DDG 2	1.23585 (5.3998)[c]	.05894 (.4799)
DDG 31	.76626 (1.4101)	-.19032 (.6527)
DDG 35	.88488 (1.6495)	.27104 (.9415)
DDG 40	-2.20916 (2.4353)[c]	-1.23961 (2.5468)[c]
FF 1036	.84500 (1.0307)	-.62049 (1.4104)

TABLE 2 (Cont'd)

Variable	C2 Effect[a]	C3/C4 Effect[a]
FF 1037	-.83358 (2.5547)[c]	-.03722 (.2126)
FF 1040	-.83242 (2.7964)[c]	-.10882 (.6813)
FF 1052	-.95217 (2.3698)[c]	.84612 (3.92438)[c]
FFG 1	1.27900 (2.686)[c]	1.16820 (4.57256)[c]
CG 16	1.55460 (4.3856)[c]	.28217 (1.4834)
CG 26	1.00975 (3.5855)[c]	.36707 (2.42908)[c]
Fleet	.092258 (5.60658)[c]	.61665 (6.98373)[c]
Constant	3.11445	.76700
Summmary Statistics		
F(27,2440)	14.76114	9.57391
R^2	.14041	.09579

Sources: Steaming and Fuel Data Master Files and Consolidated CASREPT Reporting System

[a]t-values given in parentheses.

[b]Calculated at the arithmetic means.

[c]Statistically significant at .05 level.

proportional effect. e.g., if x changes by 10 percent y also changes by 10 percent.

Elasticities of past steaming are -0.661[1] for C2 and -0.639 for C3/C4 CASREPTs, indicating there is a less than proportional but substantial effect of past steaming on the CASREPT rate.

Number of months since overhaul has a statistically significant, positive and relatively large effect. The elasticities are 0.688 for C2 and 0.831 for C3/C4 CASREPTs. As months since overhaul increase CASREPTs per month increase; but past steaming also increases which reduces the CASREPT rate. The net effect is to only slightly increase the CASREPT rate by about one C3/C4 CASREPT per year. The implication is that overhauls can be scheduled farther apart without causing serious deterioration of equipment condition.

With respect to other variables, more current steaming hours underway per month increases both C2 and C3/C4 CASREPTs, but the effect is statistically significant only for C2 CASREPTs. The elasticities are relatively low, 0.129 (C2) and 0.0125 (C3/C4). Current steaming hours not underway has a positive, relatively small but statistically significant effect on both C2 and C3/C4

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[1]Due to rounding, elasticities computed by the reader may differ slightly from those reported.

CASREPTs. Total past steaming not underway may decrease both C2 and C3/C4 CASREPTs. These effects are small and not statistically significant.

Atlantic fleet ships have statistically more C2 and C3/C4 CASREPTs than those in the Pacific fleet. Overhaul cycle variables indicate the CASREPT rate is higher in the first and perhaps second months after overhaul, so that overhauls may not fix everything they are supposed to. By contrast, CASREPT rates are lower for the last three to four months before overhual. Perhaps temporary repairs are made more often towards the end of a cycle with the expectation that permanent repairs will be made during the overhaul.

In summary, although the explanatory power of the CASREPT rate regression models is low, a number of variables are statistically significant. Our most important findings are that past steaming and time since overhaul have large effects and Atlantic fleet ships have higher CASREPT rates.

THE EFFECT OF STEAMING ON THE CASREPT RATE

Our goal is to estimate the effects of an increase in steaming using estimates of the effects of current and past steaming variables. However, there are an infinite number of ways that a given increase in steaming hours could be distributed over a ship's cycle; and the distribution would affect the value of the

past steaming variable at the midpoint of a ship's cycle where we calculate the effects of a change in steaming. To simplify calculations, we assume changes in steaming are proportional to the existing distribution of steaming hours, so that at any point in a ship's cycle, e.g., the midpoint, current and past steaming change by the same percent due to a change in steaming. Since we have partial elasticities form the same regression, we can simply add the elasticities of the current and past steaming variables to calculate the elasticity of steaming. The interested reader can use the regression findings to calculate the effects of increases in steaming that are distributed in other ways.

The sum of the elasticities of current and past steaming is given in table 3: it is -0.533 for C2 CASREPTs and -0.627 for C3/C4s. Since most of the effect is due to past steaming, we interpret the findings to mean that steaming has a beneficial effect on the CASREPT rate in the long run.[1]

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[1]A similar regression analysis was undertaken on downtime per CASREPT to determine whether it is affected by steaming, see reference [2]. There is essentially no effect of steaming on downtime per CASREPT for C2s. However, for C3/C4s downtime per CASREPT slightly increases as steaming increases. As a result, the elasticity of C3/C4 CASREPT downtime with respect to steaming is -0.39 instead of -0.63 (the elasticity of steaming with respect to the C3/C4 CASREPT rate).

TABLE 3

ELASTICITIES OF THE CASREPT RATE
WITH RESPECT TO STEAMING VARIABLES

Variable	C2	C3/C4
Current steaming	0.129	0.012
Past steaming	-0.662	-0.639
Total effect	0.533	0.627

ALTERNATIVE EXPLANATIONS OF STEAMING'S EFFECT ON THE CASREPT RATE

Steaming seems to reduce the CASREPT rate in the long run by improving levels of direct determinants. However, instead of measuring a causal relationship, the results may be spurious, a mere statistical aberration. In this subsection we analyze two ways that a spurious relationship could have been generated. Tests of the explanations yield no evidence to reject our earlier findings, and, instead, we find evidence that steaming's effect may be greater than reported earlier.

We find the beneficial effect of steaming is largely due to the effect of past steaming on the CASREPT rate. Perhaps this is because some ships are "lemons" and these do less steaming over a ship's cycle. Although low levels of past steaming would be statistically associated with high CASREPT rates, the causality would be reversed.

Another explanation may be omitted factors related to the deployment cycle. Ships steam more when deployed, but then they are also better manned. Better manning rather than steaming could be causing the beneficial effect on the CASREPT rate. A ship's crew may also look for equipment problems before deployment, and when it finds them file CASREPTs. Since these CASREPTs predate the intense steaming of deployment, few CASREPTs per month occur later in a ship's cycle. This could lead to the results we observed that past steaming reduces the CASREPT rate.[1]

These possible explanations of the results are addressed by estimating alternative CASREPT rate models. Earlier we estimated "Model 1" using time series cross section data. To adjust for ship specific factors including lemon ships, we estimate "Model 2," which is Model 1 plus dummy variables for each ship instead of 12 ship classes. These models are estimated with data on 2,500 ship-months.

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[1]Another explanation is that we are observing "reverse causality": ships with broken equipment are forced to steam less rather than steaming and factors associated with it cause reductions in the CASREPT rate. This explanation would be more believable if <u>current</u> steaming were the significant variable in the regression model. However, because the effect on the CASREPT rate is due to <u>past</u> rather than current steaming, we are probably not observing reverse causality: past steaming can affect the number of CASREPTs occuring this month, but a CASREPT this month cannot affect the amount of steaming done in the past.

We also estimate a "Model 3" using 91 cross sectional observations -- one for each ship. Here the average CASREPT rate between overhauls is the dependent variable, and, where applicable, averages of variables in Model 1 are explanantory variables. By averaging variables, Model 3 tends to eliminate the effects of deployment cycle factors.

Table 4 reports estimates of steaming's effect on the CASREPT rate for the three models. For all models, past steaming reduces the number of C2 and C3/C4 CASREPTs; however the effect is statistically significant only for Models 1 and 2. The sums of past and current steaming elasticities are fairly consistent across models: -.468 (Model 2), -.533 (Model 1), and -.678 (Model 3) for C2 CASREPTs; and -.460 (Model 2), -.627 (Model 1), and -.891 (Model 3) for C3/C4 CASREPTs.

In Models 1 and 2 most of steaming's effect is due to a relatively large past steaming elasticity. In Model 3 the elasticity of current steaming (-.506) is larger than the elasticity of past steaming (-.385), and these effects are not statistically significant for C2 or C3/C4 CASREPTS.

The reason for Model 3's results is that current and past steaming are measuring the same factor -- long-run differences in steaming rates. In Model 3 "current steaming" is average steaming hours per month between overhauls. "Past steaming" is approximately the

TABLE 4

CASREPT RATE REGRESSION RESULTS FOR STEAMING, BY MODEL AND CASREPT

CASREPT	Model	Current steaming	Past steaming	Total elasticity	R^2	$F_{N,M}$
C2	Class	0.00216	-0.00049			$F_{27,2440}$
	(t)	(5.75)[a]	(6.52)[a]		0.140	
	elasticity	0.129	-0.662	-0.533		14.76
	Ship	0.00244	-0.00046			$F_{92,237}$
	(t)	(6.79)[a]	(4.09)[a]		0.254	
	elasticity	0.146	-0.614	-0.468		8.80
	Cross section	-0.00355	-0.00033			$F_{19,71}$
	(t)	(0.60)	(1.22)		0.462	
	elasticity	-0.219	-0.459	-0.678		3.21
C3/C4	Class	0.00008	-0.00018			$F_{27,2440}$
	(t)	(0.39)	(4.40)[a]		0.096	
	elasticity	0.013	-0.639	-0.626		9.57
	Ship	0.00014	-0.00013			$F_{92,2375}$
	(t)	(0.73)	(2.19)[a]		0.181	
	elasticity	0.023	-0.483	-0.460		5.69
	Cross section	-0.00308	-0.00011			$F_{19,71}$
	(t)	(1.11)	(0.82)		0.516	
	elasticity	-0.506	-0.385	-0.891		3.98

Sources: Steaming and Fuel Data Master File and Consolidated CASREPT Reporting System.

[a]Statistically significant at .05 level.

total number of steaming hours at the mid-point of a ship's cycle. There is little independent variable between these measures, and this "multicollinearity" causes low levels of statistical significance. Nevertheless, the "message" from Model 3 is the same as that of the others. In the long run steaming reduces the CASREPT rate.

There are some differences in the size of steaming's effects across models. Which estimate is more accurate? Model 2 yielded the lowest effect of steaming. Estimates from Model 1, which are slightly larger, may be better than those from Model 2 because use of numerous ship dummy variables would tend to bias down the estimate of other variables such as steaming [14]. In Model 1 we use 12 ship class dummy variables to capture long-run differences in the CASREPT rate due to ship class specific factors. This is a compromise approach that may enable us to adjust for some ship specific factors without seriously biasing downward the effects of other included variables such as steaming.

There is a more sizable difference between the steaming elasticities from Model 1 and the larger ones obtained from Model 3, especially for C3/C4 CASREPTs. Predictions from these two models are used to help decide which yields the better estimate of steaming's effect.

Recall that Model 1 focuses on a ship's monthly CASREPT rate, while Model 3 deals with its average number of CASREPTs per month between overhauls. Focusing on different dependent variables, outputs require some adjusting to make predictions comparable. For each ship, we averaged monthly predictions from Model 1 to yield a prediction of a ship's average CASREPT rate per month between overhauls.

Comparison of average CASREPT rate predictions yields evidence in support of Model 3's higher steaming elasticity. The sum of squared errors is somewhat smaller and predictions at the tails are slightly more accurate. Since the evidence is weak, however, we decided to use the more conservative estimate of steaming's effects from Model 1, preferring to avoid possibly overstating its effect.

SUMMARY AND CONCLUSIONS

We find steaming reduces the CASREPT rate over a ship's cycle for both C2 (less serious) and C3/C4 (more serious) CASREPTs. For a typical destroyer experiencing typical steaming levels, a 25 percent reduction in steaming increases the CASREPT rate by 13 percent for C2s and 16 percent for C3/C4s. Since steaming reductions are also likely to reduce training readiness, steaming reductions clearly impair readiness.

Regression findings yield valuable insights regarding the relationship between steaming and the CASREPT rate. The total effect of steaming can be broken down into the effects of current and past steaming on the monthly CASREPT rate. We find a large beneficial effect of past steaming, which is the reason for steaming's overall beneficial effect. Since the primary factor is steaming in past months since overhaul, rather than current steaming, we interpret the findings to mean steaming reduces CASREPT downtime in the long run.

Another finding may be important for policy purposes. Only one extra C3/C4 CASREPT would be incurred on the average by delaying an overhaul for one year. That is, if a typical destroyer had, say, 20 C3/C4 CASREPTS in its third year since overhaul, it would have only 21 in its fourth year.

Two questions can be raised about the interpretation of our findings. First, perhaps there are "lemon ships" with chronic equipment problems that steam less, so CASREPTs lead to less steaming rather than the reverse. Second, are we just picking up the effects of omitted deployment cycle factors? Perhaps ships look for equipment problems before a deployment when steaming is low, or they are better manned during deployment when steaming is increased. We address these questions in turn.

To test whether lemon ships are the reason for the findings, we also estimate the CASREPT rate relationship including dummy variables for each ship. If lemon ships are causing the results, the measured effect of past steaming would be drastically reduced, but it is hardly affected by inclusion of ship dummy variables.

Concerned about omitted deployment cycle factors, we do an auxiliary analysis looking at the <u>average</u> CASREPT rate between overhauls as a function of <u>average</u> levels of factors between overhauls including hours steaming per month. By averaging variables over a ship's cycle, we reduce the possibility of spurious correlation between steaming and the CASREPT rate due to the deployment cycle. This procedure yields a <u>larger</u> estimate of steaming's effect on the CASREPT rate. Thus the results are not likely to be due to omitting deployment cycle factors, and the effect of steaming may even be larger than reported above.

While addressing many of our data problems, there is another subtle one which we cannot finesse with econometric methods. We are forced to estimate "reduced form" regression models, which do not allow us to understand the causal mechanisms through which steaming reduces the CASREPT rate. Whatever the underlying relationships between steaming and "direct determinants," e.g., better trained and more active personnel, less corrosion, fewer equipment starts, etc., we must assume they continue to hold for our estimates to be meaningful. More research on these underlying relationships is needed to provide a basis for verifying that our estimates of steaming's effects are valid today.

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